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THEORY OF

DVBLIN· COLL·SANCTÆ·ET·INDIVID·TRINITATIS

LAR ACTION.

OUTLINES

OF

A NEW THEORY OF MUSCULAR ACTION:

BEING A THESIS READ FOR THE DEGREE OF DOCTOR IN MEDICINE,
BEFORE THE UNIVERSITY OF DUBLIN, DEC. 17, 1862.

BY THE

REV. SAMUEL HAUGHTON, M.D., F.R.S.,

FELLOW OF TRINITY COLLEGE, DUBLIN.

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TO

WILLIAM STOKES, M. D.,

REGIUS PROFESSOR OF PHYSIC IN THE UNIVERSITY OF DUBLIN,

Whose readiness to devote his valuable time in aid of investigations tending to promote Medical Science is well known to all who have had occasion to seek his co-operation, this attempt to determine some of the numerical laws of Muscular Action is gratefully dedicated by

His obliged pupil and friend,

SAMUEL HAUGHTON.

TRINITY COLLEGE, DUBLIN,
March 31, 1863.

OUTLINES

OF

A NEW THEORY OF MUSCULAR ACTION,

&c. &c.

PART I.

ON THE RATE OF MUSCULAR ACTION.

In the Croonian Lecture, read before the Royal Society, on November 16th, 1809, Dr. Wollaston called attention to the sound, or susurrus, produced by the muscles when in a state of contraction. He states correctly that this sound is best produced by inserting gently the extremity of the finger into the ear, bringing at the same the muscles of the hand and forearm into strong contraction. The muscular susurrus may also be heard easily by using a stethoscope upon a contracted muscle, either of the observer's or of any other person's body.

Having described the mode of obtaining the sound, Dr. Wollaston correctly adds that it "resembles most nearly that of carriages at a great distance passing rapidly over a pavement;" to which admirable description of the sound I would add, that it bears the most striking resemblance to the deep hum produced by the blowing fan of a large foundry.

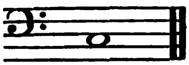
Dr. Wollaston attempted to estimate the frequency of the elementary muscular contraction that produces the susurrus by allowing his ear to rest on the ball of his thumb, while his elbow was supported by a horizontal board, in which he had cut a number of equal notches, about one-eighth of an inch asunder. Against these notches he rubbed a pencil with a regular motion, until he made the sound so produced to coincide roughly with that of the muscular contraction; and he attempted to estimate the number of notches passed over in a second. His conclusion from these comparative experiments is the following:—

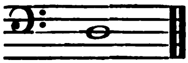
"The greatest frequency that I think I have observed was about 35 or 36 in a second, and the least was as low as 14 or 15 . . . . ; they appeared to be in general between 20 and 30 in a second; but it is possible that the method I employed may be found defective, and it is to be hoped that my estimate may be corrected by some means better adapted to the determination of intervals that cannot actually be measured."

An accidental observation made upon myself a few months ago has enabled me, I believe, to fix with the precision desired by Wollaston the rate of the muscular contraction that causes the susurrus. About three years ago, on recovering from a slight access of fever, which was fortunately cut short, I found that it left the following trace of its visit in my system:—Occasionally, since that period, when overworked by mental exertion, I have been subject to a singing in both ears, which is relieved by a drink of warm milk, and by sleep; sometimes, however, I have found the tinnitus aurium so great as to prevent sleep.

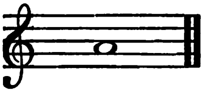
In June last (1862), while kept awake by this disagreeable noise, I amused myself with producing, by the contraction of the masseter muscles, their well-known susurrus. To my great surprise and pleasure, I observed that the tinnitus and susurrus were in unison, differing from each other by several octaves.

I followed up the clue thus found, and consulted my musical friends, whom I instructed in the mode of making Wollaston's experiment, without, however, informing them of the note that I myself believed to be the true sound of the susurrus and tinnitus. My friends have arranged themselves into two groups, which have fixed upon CCC and DDD, respectively, as the note of their susurrus—that is to say, two octaves below bass C and D

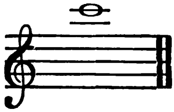




These notes are found on the new pianos only, and several of my friends informed me that the C or D, the lowest on their piano, was an octave above the susurrus; but, on inquiry, there was no difficulty in ascertaining what note was really indicated. The tuning of the pianos was carefully tested with a standard CC diapason, of 64 double vibrations per second, used for acoustical experiments, and corresponding with 426⅓ vibrations in the second for the note, treble A.



Four of the observers, of whom two were ladies, found CCC, and five, of whom three were ladies, found DDD, which notes correspond, respectively, to thirty-two and thirty-six vibrations in the second.

To my own ear, the susurrus has constantly the sound of CCC; and the tinnitus had, on the morning of 30th June, 1862, the sound of the octave above treble C, that is to say, it was ;* five octaves above the susurrus, and therefore corresponding to a rate of vibration thirty-two times faster than that of the muscle, or 1024 times in the second.

---

* This is the note given out by a well-formed hand bell, of 4 inches diameter.

The tinnitus is altogether independent of muscular or voluntary action of any kind, and is, I believe, a sign of the rate at which nervous action takes place in the brain. This conjecture I hope at some future time either to verify or disprove. The sound of the muscular susurrus, when fully heard, is ridiculously like the sound of the cab-wheels of London heard in the silence of the night, when the absence of thoroughfare in the streets enables the cabmen to drive fast. I have measured the intervals of the Guernsey granite pavement, and found them to be about four inches, making therefore three impulses in a foot traversed by the cab-wheels. If the cabs be supposed to drive eight miles an hour, the number of impulses per second will be

$$\frac{5280 \times 3 \times 8}{3600} = 35{\cdot}2.$$

Considering that the standard DDD of the susurrus is thirty-six vibrations per second, its resemblance to the sound of cab-wheels ceases to be a matter of surprise. In order to determine the sound of the susurrus precisely, I procured a long wooden tube, 3 inches by 2½ inches inside, like an organ-pipe, fitted with a moveable piston, so that on applying it to an acoustical bellows, on moving* the piston in or out, I could produce any note I pleased, in the neighbourhood of CCC. This pipe is tuned, by means of the piston, to the susurrus of any observer, and then played in conjunction with the standard CCC, and the beats counted if it be not in unison.

---

* The piston is moved in the acoustical tube by means of an endless chain movement, made for me by Mr. Spencer, of Aungier-street.

Let m denote the number of vibrations per second in the standard pipe, n the corresponding number in the tuned susurrus pipe, or *vice versâ*, so that m shall be greater than n, and let k be the number of beats per second counted on playing the two pipes together; then it is easily shown that

$$k = m - n. \tag{1}$$

As an example of this principle, I take the following observation:—

Dr. William Stokes, of this city, kindly aided me in my investigations upon one occasion, by tuning the wooden pipe to the susurrus observed in himself, leaning both his elbows on a table, with the muscles of the fore-arms contracted, and making the sound of the pipe coincide with the susurrus when heard together by both ears.

On comparing the note he fixed on, with the standard CCC, it was found to be higher than it to such an extent as to produce fifty beats in fifteen seconds.

Hence,

$$\frac{50}{15} = m - 32 ; \text{ or}$$

$$3\tfrac{1}{3} = m - 32 ;$$

and, finally,

$$m = 35\tfrac{1}{3} \text{ vibrations per second.}$$

This is DDD natural, a little flat; for DDD corresponds to thirty-six vibrations in the second.

PART II.

ON THE AMOUNT OF WORK STORED UP IN HUMAN MUSCLES.

HAVING found, within narrow limits, the rate at which muscular contraction takes place, I proceeded to find the quantity of work stored up in muscle, in the following manner:—

If both arms be extended horizontally, they are kept from falling, each by the action of two muscles only, the supra spinatus and the central portion of the deltoid of each shoulder.

Great relief is felt on either raising or lowering the arms, above or below the strictly horizontal position; this relief being due to the fact that the trapezius, in the first case, or the biceps, in the latter case, comes into play to assist the other two muscles, if the arms deviate from the horizontal position.

I found that my own arms became completely tired at the end of seven minutes, and I thus attempted to determine the amount of work given out during that time by the two muscles in question.

Each portion of the muscle contracts, relaxes, and goes through all its changes thirty-two times in each second, and does so in succession, so as to keep the ends of the fingers steady; but the amount of work given out by the whole muscle is evidently the same as if all the particles went through their changes simultaneously, and not in succession.

If the whole muscle acted simultaneously, the arm would fall like a compound pendulum during the $\frac{1}{32}$nd part of a second, and then be raised to its original level by the renewed contraction of the muscle.

It is not difficult to prove that in this case the arc through which the arm falls is that which would correspond to the centre of oscillation falling freely for $\frac{1}{32}$nd of a second. But a body falling freely for $\frac{1}{32}$nd of a second will pass through $\frac{1}{64}$th of a foot, or $\frac{3}{16}$ths of an inch. This is, therefore, the space fallen through in each relaxation of the muscle, by the centre of oscillation of the arm.

Assuming, as an approximation, that the arm and clenched fist form a uniform cylinder, their centre of oscillation would be distant from the centre of the glenoid cavity, two-thirds of the length from the tip of the acromion process to the metacarpo-phalangeal articulation of the middle finger. In my arm this length is 24 inches, which would give 16 inches as the length of the equivalent simple pendulum.

From the tip of the acromion process to the fold of the elbow, which I believe to be the centre of gravity of the arm, is 11 inches; and therefore, as the centre of oscillation descends through $\frac{3}{16}$ths of an inch during each $\frac{1}{32}$nd part of a second, the centre of gravity will in the same time fall through $\frac{11}{16} \times \frac{3}{16}$ths of an inch.

The weight of the arm may readily be found by weighing it in a balance whose scale is on a level with the centre of the glenoid cavity, and treating it as a lever, so that the weight of the arm shall be to the weight that supports any point of the arm inversely as the distances of the centre of gravity and of that point from the centre of the glenoid cavity. By observations made in this way I found my arm to weigh 7½ lbs.

Therefore the supra spinatus and deltoid lifted during each interval of $\frac{1}{32}$nd of a second 7½ lbs. through $\frac{11}{16} \times \frac{3}{16}$ths of an inch; and in seven minutes, at the end of which time the muscles were exhausted, the work done by them was,

$$7\tfrac{1}{2} \times \tfrac{11}{16} \times \tfrac{1}{64} \times 32 \times 60 \times 7 \text{ ft. lbs.} = 1082{\cdot}8 \text{ foot pounds.}$$

These muscles are therefore capable, in each of my shoulders, of giving out work equivalent to raising 1083 lbs. through a foot, before they become exhausted.

Mr. Arthur W. Foot, M.B., assisted me in most of my experiments, and possesses supra spinati and deltoids capable of somewhat more work than mine.

The data for Mr. Foot's case are:—

Weight of arm, 7 lbs.

Tip of acromion to metacarpo-phalangeal articulation, 24½ inches.

Tip of acromion to fold of elbow, 11½ inches.
Time of exhausting muscles, 8 minutes.
Hence I find the work done to be

$$7 \times \frac{11 \cdot 5}{16 \cdot 3} \times \frac{1}{64} \times 32 \times 60 \times 8 \text{ ft. lbs.} = 1185 \text{ foot pounds.}$$

I should add, that I believe Mr. Foot carried the exhaustion of the muscles further than I did in his experiment, as he suffered from subacute pain in the supra spinati for half an hour after the experiment was over.

I have found the following results on several persons required to hold both arms perfectly horizontally, with the palms of the hands directed upwards:—

	Weight of arm.	Time of exhaustion of muscles.
1. Self,	7·5 lbs.	7 minutes.
2. Mr. A. W. Foot,	7 „	8 „
3. Mr. S.,	—	9 „
4. Mr. I.,	—	9 „
5. Mr. P.,	—	6·5 „
6. Dr. W.,	—	10 „
	Mean,	8·25 minutes.
1. S. H., æt. 13,	—	15 „
2. F. S., æt. 14,	—	15 „
3. J. H. S., æt. 12,	—	10 „
	Mean,	13·33 minutes.
1. Mrs. S.,	—	12 „
2. Miss H.,	—	7·5 „
	Mean,	9·75 minutes.

From the preceding Table it would appear that in boys and women the endurance of these muscles is greater than in men, although it is well known that they are not capable of so great an exertion of force at a given moment. Taking a mean of my own and of Mr. Foot's muscles, I find that the supra spinati and central portion of the deltoids of both sides are capable of lifting 2268 lbs. through one foot, before they become exhausted—that is to say, very nearly one ton lifted through one foot.

It was now necessary for me to find the weight of the muscles concerned in doing this amount of work, which I proceeded to determine as follows :—

Having selected a well-developed male subject, aged 45, and weighing 130 lbs., I carefully dissected the muscles of his right shoulder, and found that the deltoid was readily divisible into three portions, of which the central only was concerned in holding the arm in the horizontal position; in fact, the whole work was done by this portion of the deltoid and by the supra spinatus muscle. The weights of the muscles I examined were found to be as follows :—

1. Central portion of deltoid, ...	3⅜ oz.	5⅛ oz.
2. Supra spinatus, ...	1¾ „	
3. Internal or clavicular portion of deltoid, .	1⅜ „	
4. External portion of deltoid, from spine of scapula, and part of acromion process,	5½ „	
5. Biceps humeri, ...	4 „	
6. Coraco-brachialis, ...	1¾ „	

Hence it appears that the weight of the muscles on both sides, engaged in the act of holding up the arms exactly in the horizontal position, is 10¼ oz., or 4485 grs.; but as this weight of muscle was proved capable of lifting one ton through a foot, before it became exhausted, it follows by an easy calculation that 1 lb. weight of the same kind of muscle is capable of lifting 1·56 ton through one foot.

PART III.

ON THE WORK DONE, IN A DAY, BY THE HUMAN HEART.

FROM auscultation of the first sound of the heart, I am satisfied that it gives the same musical tone as the other muscles of the body; and as it never becomes wearied, it is a matter of some physiological interest to calculate the amount of work done by it during the day.

From the following estimates of the weight of the heart, a mean must be deduced, which is then to be used in our calculation:—

Table of Average Weight of Human Heart.

	Oz.
1. Meckel,	10·0
2. Cruveilhier,	7·5
3. Bouillaud,	8.375
4. Lobstein,	9·5
5. Boyd [æt. 30–40],	10·41
6. Boyd [æt. 40–50],	10·56
	Mean = 9·39 oz.

From this weight, combined with the previous determination of the work stored up in the ordinary muscles, I obtain the following chain :—

$$\begin{array}{rl} & 9{\cdot}39 \text{ oz. of heart.} \\ 10.25 & 2268 \text{ ft. lbs.} \\ 2240 & 1 \text{ ft. tons.} \\ \hline & \mathbf{0{\cdot}9275} \text{ ft. ton.} \end{array}$$

If the heart, therefore, were an ordinary muscle, it would lift 0·9275 of a ton through a foot in 7½ minutes, and then become incapable of doing more work for some time. As the heart, however, never tires, it accomplishes this amount of work in 7½ minutes, and eight times this work in one hour; therefore in twenty-four hours, the

$$\begin{aligned} \text{Work done by heart} &= 0{\cdot}9275 \times 8 \times 24. \\ &= \mathbf{178{\cdot}09} \text{ ft. tons.} \end{aligned}$$

During each double beat of the heart, reckoned as 10 parts of time, seven parts are occupied by a muscular contraction of the ventricles or auricles, and three parts are not employed in doing mechanical work; reducing, therefore, the work just calculated to $\frac{7}{10}$ths of its amount, I find the

$$\text{Daily work of heart} = \mathbf{124{\cdot}6} \text{ ft. tons.}$$

I have elsewhere* shown that the labouring force of man is less than 400 tons lifted per day; as may be seen from the following Table :—

---

* "Manual of Mechanics," p. 106, *et seq.*

Labouring Force of Man.

No.	Kind of work.	Amount of work.	Authority.
1	Pile driving, ...	312 ft. tons.	Coulomb.
2	Pile driving, ...	352 „	Lamandé.
3	Turning a winch, ...	374 „	Coulomb.
4	Porters carrying goods, and returning unloaded, ...	325 „	Coulomb.
5	Pedlars always loaded, ...	303 „	Coulomb.
6	Men walking unloaded, ...	353 „	Haughton.
7	Porters carrying wood up a staircase, and returning unloaded,	381 „	Coulomb.
8	Paviours at work, ...	352 „	Haughton.
9	Prisoners at shot drill, and oakum-picking, ...	310 „	Haughton.
	Mean, ...	340·2 ft. tons.	

In forming the preceding Table, I have corrected Coulomb's and Lamandé's estimates of useful work, so as to bring in the weight of the labourer, and the fatigue work as well as the useful work.

It appears from a comparison of the calculation of the work of the heart with the preceding Table, that it is more than one-third of the daily labouring force of the whole body.

No reflecting mind can avoid feeling the highest admiration and reverential awe of the Divine Hand that has formed a mechanism so wonderful, that in a single day it can weary out nearly 200 times its own weight of the stanchest muscles of the body; and itself rarely tires, unless the progress of some disorder foreign to it clogs its movements, the last pulse of which corresponds with systemic death, which is speedily followed by the cessation of the somatic life, the continuance of which, after systemic death, is but the last faint echo of the footfalls of the heart, which rapidly die away when that wonderful machine itself has become silent for ever.

Note added on the 20th of March, 1863.—The calculation of the amount of work done by the heart in a day, which I have given in the preceding paper, although based on accurate observations of the work done by other muscles, yet appeared to me to require confirmation from independent considerations, without which I could scarcely hope that physiologists in general would attribute to it the same degree of value that I did myself. I had therefore attempted to calculate this same quantity, the daily work of the heart, from hydraulic principles, founded on the well-known hæmastatic experiments of Dr. Hales; but was unable to complete my calculations, in consequence of not knowing the requisite constants for the hydrostatic pressure of the human heart.

The Rev. Dr. Hales' experiments were made on horses, dogs, oxen, sheep, and deer; and he never had an opportunity of performing similar experiments on man; but an accidental circumstance has, within the last few days, enabled me to make an observation on the human subject, equivalent to an experiment, and thus to fill up an important gap in his classical experiments, and at the same time to obtain an independent means of estimating the daily work of the human heart, and thus to check the numerical result at which I have arrived already from totally different principles.

The unknown quantity, which must be found before this estimate of the heart's work can be made, is the hydrostatical pressure inside the left ventricle of the human heart during life.

Dr. Hales' experiments on animals consisted in opening a large artery, the crural or carotid, inserting a brass or glass tube into the opening, and observing the height at which the blood stood in the vertical tube; the animal was then killed by the gradual abstraction of blood, and the height noted after each loss of blood.

The following Table contains his results for horses:—

No.	Artery.	Blood lost.	Height in tube.
1. Mare,	Left crural,	0 qts. 5 oz.	8 ft. 3 in.
	,,	9 qts.	3 ft. 10 in.
	,,	16 qts.	2 ft. 4 in.
2. Gelding,	Left crural,	0 qts. 1 pt.	9 ft. 8 in.
	,,	9 qts.	6 ft. 6½ in.
	,,	15 qts. 1 pt.	2 ft. 10 in.
3. Mare,	Left carotid,	70 cub. in.	9 ft. 6 in.
	,,	490 ,,	3 ft. 4½ in.
	,,	833 ,, 14·4 qts.	2 ft. 5 in.

The animals all expired when the height of blood fell to about 2½ feet, at which time the blood was nearly drained out of the vessels. Taking the means, I find,

Height before serious loss of blood = 9·14 ft.
Height at close of experiments = 2·53 ft.

The first of these heights denotes the hydrostatical pressure inside the left ventricle, when the vessels are all filled with blood, and when, in order to overcome their hydraulic resistance, the heart is obliged to exert a force measured by 9·14 feet of blood.

The second height denotes the hydrostatical pressure exerted by the heart when the vessels are empty, and when, therefore, the blood may be regarded as spouting into an almost empty vessel.

Dr. Hales notices, in his first experiment—"Then I took away the glass tube, and let the blood from the artery mount up in the open air, when the greatest height of its jet was not above two feet."—Statical Essays, vol. ii. p. 2.

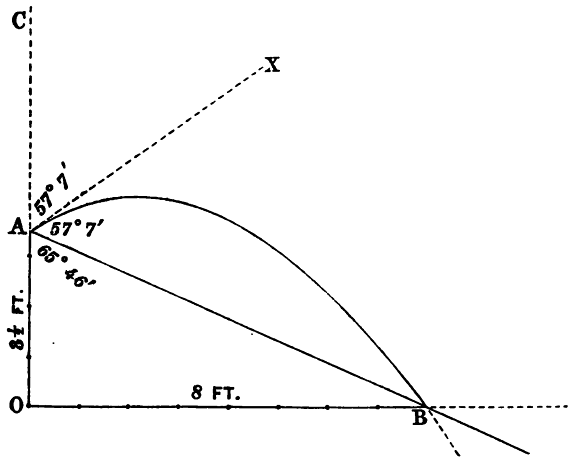
This observation has been confirmed by subsequent experiments of Allen Thomson and Dick, who found the greatest height of the vertical jet of blood not to exceed three feet.

We may safely take 2·53 feet as the height to which the blood, issuing from a large artery in the horse, would spout vertically. The corresponding height in man, I can determine with precision in the following manner:—

On the 18th of March, a large fibro-cellular tumour was removed by Mr. M. H. Colles, in the operating theatre of the Meath Hospital, from the left groin of a middle-aged, large-sized man; in the course of the operation the external epigastric artery, which appeared enlarged to feed the tumour, was divided, and before it could be ligatured, strong jets of blood from it were thrown in various directions about the room. I noticed, as the poor fellow moved about on the operating table, that the jets of blood fell short, or enjoyed a long range, according to the angle of elevation of the orifice of the bleeding artery, and that there was a certain maximum range on the floor of the theatre, which was not exceeded.

I saw immediately that I had before my eyes the solution of the problem that had puzzled me; as by measuring the co-ordinates of the maximum range, I could calculate the velocity with which the blood left the artery.

In the annexed figure, which is drawn to scale, let A represent the orifice of the artery, and B the position of the farthest squirt of blood on the floor; OA was found to be 3 ft. 6 in., and OB was 8 ft. It is well known that AX, the direction of projection of



the maximum range on the plane AB, bisects the angle CAB,* and that

$$h = \frac{R \cos^2 i}{4 \cos^2 e}; \qquad (2)$$

where

h = the unknown height due to the velocity of projection;

R = the maximum range AB = 8·773 ft.

i = the angle made by AB with the horizon = 24° 14′;

e = the angle of elevation, made by AX with the horizon = 32° 53′.

Substituting the preceding values in equation (2), I find,

$$h = 2·586 \text{ ft};$$

and since the velocity of projection, v, is given by the equation,

$$v = \sqrt{2gh}; \qquad (3)$$

it follows that

$$v = 12·905 \text{ ft}.$$

*** Galbraith and Haughton's "Manual of Mechanics," p. 169.**

I have already shown that Hales found for the large arteries of the horse,

$$h = 2{\cdot}53 \text{ ft.}$$

This corresponds so closely with the result just found by observation on the human subject, that I think myself entitled to conclude that the hydrostatical pressure in the unopened arteries and left ventricle in man,* is also the same as in the horse, viz., 9·14 ft. of blood, or very nearly 110 inches, And as each cubic inch of blood weighs 268 grains, this is equivalent to a pressure of

$$29{,}480 \text{ grs.} = 4{\cdot}211 \text{ lbs.}$$

on each square inch of the inside of the left ventricle.

At every beat of the heart, 3 oz. of blood are propelled against this pressure, through the aorta; let a denote the area of this vessel, x the distance through which the blood is propelled, and F the propelling force; then,

$$F = 4{\cdot}211\, a,$$

and the work done in a single beat is

$$Fx = 4{\cdot}211\, ax. \tag{4}$$

To make use of this equation, we need not know either a or x, for the product ax is the number of cubic inches in 3 oz., which is very nearly $5\frac{1}{3}$.

---

* Hales estimates this pressure in man at $7\frac{1}{3}$ ft., without assigning *any reason* for his opinion.

Taking 75 beats per minute as the average, and converting the pounds and inches into tons and feet, we have,

$$\text{Work of left ventricle in 24 hours} = \frac{4{\cdot}211 \times 5{\cdot}2 \times 75 \times 60 \times 24}{2240 \times 12}$$
$$= 87{\cdot}98 \text{ ft. tons.}$$

I find, on taking an average of the estimates of Bouillaud, Laennec, Cruveilhier, Sömmering, and Andral, that the right ventricle has a thickness, which is to that of the left in the proportion of 5 to 13; and as the cavities are of equal dimensions, the thicknesses are proportional to their muscular powers; in order, therefore, to find the total work done by the heart, we must add to the preceding result $\frac{5}{13}$ths of its amount, from which we obtain, finally,

Daily work of left ventricle = 87·98 ft. tons.
Daily work of right ventricle = 33·84 „

Total daily work of heart = **121·82** ft. tons.

On comparing this, which may be considered as the Hydraulic work of the heart, with the Muscular work of the heart (**124·6** ft. tons), already deduced from totally different considerations, their agreement must be regarded as a remarkable confirmation of the theory of muscular action on which the first calculation was founded.

THE END.